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Slow Crack Growth of Brittle Materials With Exponential Crack-Velocity Formulation—Part 3: Constant Stress and Cyclic Stress Experiments

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Summary

The previously determined life prediction analysis based on an exponential crack-velocity formulation was examined using a variety of experimental data on advanced structural ceramics tested under constant stress and cyclic stress loading at ambient and elevated temperatures. The data fit to the relation between the time to failure and applied stress (or maximum applied stress in cyclic loading) was very reasonable for most of the materials studied. It was also found that life prediction for cyclic stress loading from data of constant stress loading in the exponential formulation was in good agreement with the experimental data, resulting in a similar degree of accuracy as compared with the power-law formulation. The major limitation in the exponential crack-velocity formulation, however, was that the inert strength of a material must be known a priori to evaluate the important slow-crack-growth (SCG) parameter n, a significant drawback as compared with the conventional power-law crack-velocity formulation.

Introduction

Advanced ceramics are candidate materials for structural applications in advanced heat engines and heat recovery systems. The major limitation of these materials in hostile environments, particularly at elevated temperatures, is slow-crack-growth (SCG)-associated failure, where slow crack growth of inherent defects or flaws can occur until a critical size for catastrophic failure is reached. To ensure accurate life prediction of ceramic components, it is important to accurately evaluate SCG parameters of a material with specified loading and environmental conditions.

Life prediction (or SCG) parameters of a material depend on what type of crack-velocity formulation is used to determine them. The power-law crack-velocity formulation has been used for several decades to describe SCG behavior of a variety of brittle materials ranging from glass to glass ceramics to advanced structural ceramics. The primary advantage of the power-law formulation over other crack-velocity formulations is the simplicity in its mathematical expression for lifetime analysis. It has also been observed that the power-law formulation has adequately described the SCG behavior of many brittle materials. Because of these merits, the power-law formulation has been used in two recent ASTM test standards (refs. 1 and 2) to determine SCG parameters of advanced ceramics in constant stress rate testing at both ambient and elevated temperatures. Alternative crack-velocity formulations take exponential forms to account for the influence of other phenomena (such as a corrosion reaction, diffusion control, thermal activation, etc.). However, these exponential forms in general do not result in simple mathematical expressions of life prediction formulation, although the forms might better represent the actual SCG behavior of some materials. Because of this mathematical inconvenience, the exponential crack-velocity formulation has rarely been used for brittle materials as a means of life prediction methodology in testing or analysis.

In part 1 of this report (ref. 3), the exponential crack-velocity formulation was analyzed to achieve a more convenient and simplified life prediction analysis using three widely utilized load configurations including constant stress rate (dynamic fatigue), constant stress (static fatigue), and cyclic stress (cyclic fatigue). The resulting analysis obtained with the exponential formulation was compared with that of the power-law formulation to assess which would yield a better life prediction methodology in terms of accuracy and convenience. The analysis of constant stress rate loading was scrutinized in part 2 of this report (ref. 4) using a variety of experimental data on constant stress rate and preloading tests at both ambient and elevated temperatures. The overall accuracy of analysis in conjunction with experimental data was very reasonable; however, the requirement of having accurate inert strength data to determine the major SCG parameter n gave rise to a significant limitation in using the exponential formulation rather than the conventional power-law formulation. As an extension of previous work (refs. 3 and 4), this report will describe the exponential formulation and its experimental verification in both constant stress and cyclic stress loading configurations. The SCG data for various advanced ceramics at both ambient and elevated temperatures were utilized for this purpose in terms of the degree of data fitting as well as of the accuracy of life prediction from one loading configuration to another.

All symbols used in this report are listed in the appendix.

This work was sponsored in part by the High Operating Temperature Propulsion Components (HOTPC) and the Zero CO_2 Emission Technology (ZCET) projects at the NASA Glenn Research Center, Cleveland, Ohio.

Theoretical Background

The results of the previous SCG analysis (ref. 3) using the exponential crack-velocity formulation will be briefly presented in this section for the cases of constant stress and cyclic stress loading. The companion SCG analysis using the conventional power-law velocity formulation will also be included here for comparison and generalization of the analysis.

Power-Law SCG Formulation

The widely utilized empirical power-law crack velocity above the fatigue limit is expressed in the following familiar form:

$$v = \frac{\mathrm{d}a}{\mathrm{d}t} = A\left(\frac{K_I}{K_{IC}}\right)^n \tag{1}$$

where

v	crack velocity
a	crack size
t	time
K_I	mode I stress intensity factor
K_{IC}	mode I critical stress intensity factor (or fracture toughness)
A, n	material- and environment-dependent SCG parameters

Constant stress and cyclic stress testing are performed by applying, respectively, constant stress and cyclic stress to ground-test specimens to determine the corresponding time to failure. The time to failure in constant stress and cyclic stress tests can be analytically derived to give the following familiar relations (refs. 5 and 6):

$$t_{fs} = D_s \sigma^{-n} \tag{2}$$

$$t_{fc} = D_c \sigma_{\max}^{-n} \tag{3}$$

where t_{fs} is time to failure in constant stress testing subjected to a constant applied stress σ, and t_{fc} is time to failure in cyclic stress testing whereby the material is subjected to cyclic loading with a maximum stress $\sigma_{\max}$. The parameters D can be expressed as follows (refs. 5 and 6):

$$D_s = BS_i^{n-2} \tag{4}$$

$$D_c = \frac{BS_i^{n-2}}{\frac{1}{\tau}\int_0^{\tau}[f(t)]^n \, \mathrm{d}t} \tag{5}$$

where S_i is the inert strength whereby no slow crack growth occurs; $B = 2K_{IC}/AY^2(n-2)]$ where Y is the crack geometry factor in the relation of $K_I = Y\sigma a^{1/2}$ where σ is remote applied stress; $f(t)$ is a periodic function in cyclic loading specified in $\sigma(t) = \sigma_{\max} f(t)$ in a range of $0 \le f(t) \le 1$; and τ is the period. The slow-crack-growth parameters n and D (and B or A) can be obtained by a linear regression analysis with experimental data in conjunction with the corresponding equation, (2) or (3), depending on the type of loading. Hence, it is straightforward to determine SCG parameters n and D by least-squares fitting of the data, which is the most advantageous feature of the power-law crack-velocity formulation. This convenience and merit in mathematical simplicity in addition to the use of routine test techniques have led for several decades to the almost exclusive use of the power-law crack-velocity formulation in life prediction analysis and testing for many brittle materials over a wide range of temperatures.

Exponential SCG Formulation

Several exponential crack-velocity formulations that have been previously proposed are based on other factors including chemically assisted corrosion reaction (ref. 7), diffusion-controlled stress rupture (ref. 8), thermally activated process (ref. 9), chemical reaction with constant crack-tip configuration (ref. 10), kinetic crack growth (ref. 11), and others (ref. 12). The generalized exponential crack-velocity forms thus proposed are

$$v = A \exp\left[n\left(\frac{K_I}{K_{IC}}\right)\right] \tag{6}$$

$$v = A\left(\frac{K_I}{K_{IC}}\right)\exp\left[n\left(\frac{K_I}{K_{IC}}\right)\right] \tag{7}$$

$$v = A\left(\frac{K_{IC}}{K_I}\right)\exp\left[n\left(\frac{K_I}{K_{IC}}\right)\right] \tag{8}$$

$$v = A\exp\left[n\left(\frac{K_I}{K_{IC}}\right)^2\right] \tag{9}$$

$$v = A\left(\frac{K_I}{K_{IC}}\right)\exp\left[n\left(\frac{K_I}{K_{IC}}\right)^2\right] \tag{10}$$

where A and n are SCG parameters and are different from those used in the power-law formulation.

Unlike the power-law crack-velocity formulation, the exponential crack-velocity forms do not yield simple analytical expressions either of the resulting strength as a function of applied stress rate in constant stress rate testing or of the resulting time to failure as a function of the applied stress in constant stress testing or the maximum applied stress in cyclic stress testing. Several attempts have been made under both constant stress rate and constant stress loading to obtain corresponding lifetime expressions through numerical integration incorporating with linear (refs. 13 and 14) or nonlinear (ref. 15) regression analysis. However, this approach still involves complexity in regression technique, as compared to the simple least-squares approach in the power-law formulation.

Slow crack growth analyses of three load configurations of constant stress rate, constant stress, and cyclic stress loading were made in the previous work (ref. 3). More convenient, simpler formulations were obtained through numerical approaches. It was found that little difference in SCG formulation existed among equations (6) to (8) and that equation (6) was regarded as a representative exponential crack-velocity form. Hence, equation (6) was exclusively used in the previous analysis. To minimize the number of parameters to be specified (such as A, a, σ, S_i, K_{IC}, and t), it is convenient to use a normalized scheme, as used previously for the power-law velocity formulation (refs. 16 to 18):

$$K^* = \frac{K_I}{K_{IC}};\quad T^* = \frac{A}{a_i}t;\quad C^* = \frac{a}{a_i};\quad \sigma^* = \frac{\sigma}{S_i};\quad \sigma^*_{\max} = \frac{\sigma_{\max}}{S_i} \tag{11}$$

where

K^*	stress intensity factor (SIF)
T^*	time
C^*	crack size
σ^*	applied stress
$\sigma^*_{\max}$	applied maximum stress

and a_i is the critical crack size in the inert condition or is the initial crack size. Using these variables, the exponential crack-velocity equation (6) can be normalized as

$$\frac{dC^*}{dT^*} = e^{nK^*} \tag{12}$$

The corresponding normalized SIF, K^* is expressed in constant stress and in sinusoidal cyclic loading, respectively, as follows:

$$K^* = \sigma^* \left(C^*\right)^{1/2} \tag{13}$$

$$K^* = \left\{\frac{1+R}{2} + \frac{1-R}{2}\sin\left[\left(\frac{\omega a_i}{A}\right)T^*\right]\right\}\sigma^*_{max}\left(C^*\right)^{1/2} \tag{14}$$

where R is the stress (or load) ratio, defined as $R = \sigma_{min}/\sigma_{max}$, where σ_{min} and σ_{max} are the minimum and maximum applied stresses, respectively, in sinusoidal cyclic loading, and ω is the angular velocity. As typical of ceramics, the crack size at instability in either an inert or fatigue environment was assumed to be small compared with the body of the specimens or components (i.e., an infinite-body assumption). The differential equation (12) was solved numerically using a fourth-order Runge-Kutta method for each respective loading configuration. The initial condition was $C^* = 1.0$ at $T^* = 0$, and the instability condition was $K^* = 1.0$ and $dK^*/dC^* > 0$. In cyclic loading, the frequency was taken as arbitrary values of $\omega a_i/A \geq 10^8$, depending on the values of maximum applied stress and n. The effect of frequency on solution was found to be independent in part 1 of this study (ref. 3).

Constant stress loading.—The numerical results of normalized time to failure T_f^* as a function of normalized applied stress σ^* are shown in figure 1, where $\ln T_f^*$ was plotted against σ^* for values of n ranging from 5 to 100. The general trend of the solution can be summarized in terms of the convergence of $\ln T_f^*$ close to zero with $\sigma^* \to 0$, the increased SCG susceptibility with decreasing n values, and the linearity between $\ln T_f^*$ and σ^* in the range of σ^* from 0.2 to 0.9. As a consequence, the relationship between normalized time to failure and normalized applied stress within the linear region can be written as

$$\ln T_f^* = -n'\sigma^* + \beta \tag{15}$$

where n' is the slope or apparent (calculated) SCG parameter, and β is the intercept. The linearity between $\ln T_f^*$ and σ^* was obvious when the correlation coefficient of $r^2 \geq 0.995$ for each curve was considered. Hence, the slope n' and intercept β can be determined with reasonable accuracy by a linear regression analysis of the numerical results based on equation (15). The relationship between the calculated apparent SCG parameter n' and the true SCG parameter n (an input datum) is

$$n' = 0.9827n + 3.3440 \tag{16}$$

with $r^2 = 0.9997$. The difference between n' and n was ≥8 percent for $n \leq 30$ and ≤5 percent for $n \geq 40$ so that a further approximation of equation (16) is made for the case of $n \geq 40$ as follows:

$$n' \approx n \tag{17}$$

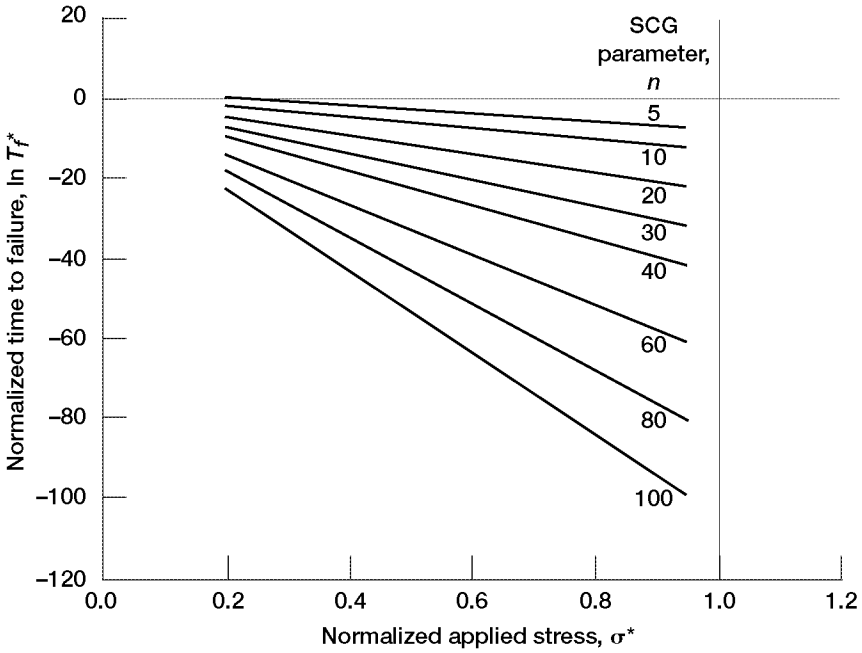

Figure 1.—Numerical results of normalized time to failure T_f^* as function of normalized applied stress σ^* in constant stress loading for different values of SCG parameters n in exponential crack-velocity formulation.

The intercept β is dependent on n:

$$\beta = -1.913 + 4.985\,e^{-0.049n} \tag{18}$$

with $r^2 = 0.9907$.

For the nonnormalized expression, equation (11) is used to reduce equation (15) to

$$\ln t_f = -n'\frac{\sigma}{S_i} + \chi \tag{19}$$

where t_f is time to failure and

$$\chi = \ln\left(\frac{a_i}{A}\right) + \beta \tag{20}$$

Therefore, the SCG parameters n' and χ in constant stress loading can be obtained from the slope and intercept, respectively, by a simple linear regression analysis of experimental data of ln t_f as a function of σ or σ/S_i. With n' determined, the true SCG parameter n can be evaluated from equation (16). The SCG parameter A can be estimated from equation (20) from calculated χ together with β (eq. (18)) and a known value of a_i. A notable difference in constant stress loading between the power-law and exponential formulations is that in the power-law formulation, t_f is a function of σ as seen in equation

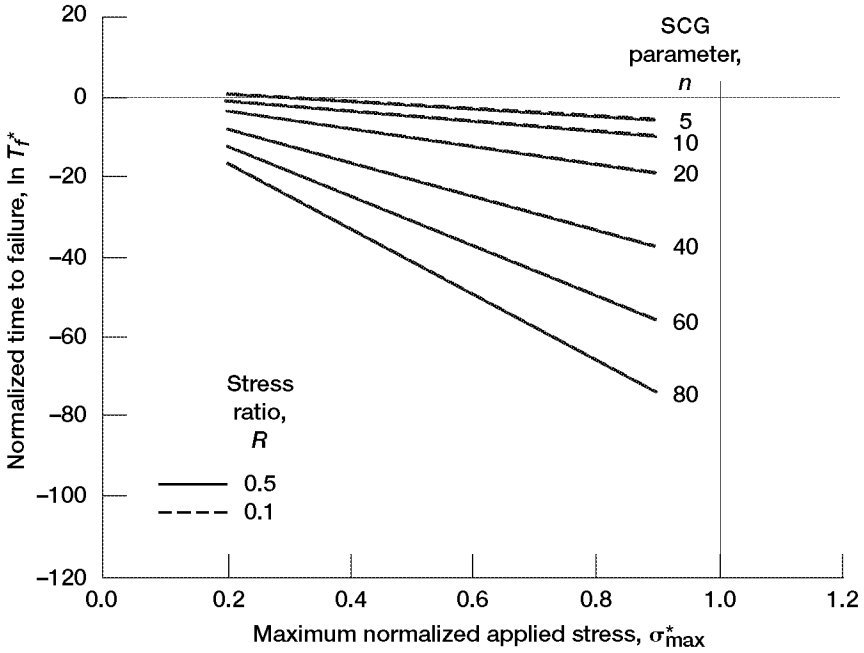

Figure 2.—Numerical results of normalized time to failure T_f^* as function of normalized maximum applied stress σ^*_{max} in sinusoidal cyclic loading for different values of SCG parameters n in exponential crack-velocity formulation.

(2); however, in the exponential formulation, ln t_f is a function of σ or σ/S_i as seen in equation (19). Hence, inert strength must be known to determine the major SCG parameter n, which would be a distinctive drawback of the exponential formulation compared with the conventional power-law formulation.

Cyclic stress loading.—The results of the numerical solution of normalized time to failure T_f^* as a function of maximum normalized applied stress σ^*_{max} in sinusoidal cyclic loading with stress ratios $R = 0.1$ and 0.5 are shown in figure 2, where ln T_f^* was plotted against σ^*_{max} for values of n ranging from 5 to 80. Similar to the case of constant stress loading, ln T_f^* is linear with respect to σ^*_{max} in the range 0.2 to 0.9 and converges close to zero with further decreasing maximum normalized applied stress. The linearity between ln T_f^* and σ^*_{max} is evident considering that the correlation coefficient $r^2 \geq 0.997$. Hence, the relationship between ln T_f^* and σ^*_{max} can be expressed as

$$\ln T_f^* = -n'\sigma^*_{max} + \beta \tag{21}$$

where n' is the slope or apparent SCG parameter and β is the intercept, which can be determined from the numerical results using a linear regression analysis based on equation (21).

The relationship between the calculated apparent SCG parameter n' and the true SCG parameter n for $R = 0.1$ and 0.5 showed the following relations with $r^2 > 0.999$:

$$\begin{aligned} n' &= 0.9777n + 2.5296 \quad \text{for } R = 0.1 \\ n' &= 0.9772n + 2.5411 \quad \text{for } R = 0.5 \end{aligned} \tag{22}$$

Because the difference between n' and n was ≥7 percent for $n \leq 20$ and ≤3 percent $n \geq 40$, a further approximation of equation (22) can be made for $R = 0.1$ and 0.5 for the case of $n \geq 40$:

$$n' \approx n \tag{23}$$

The relationship between β and n was

$$\begin{aligned} \beta &= 0.1409 + 3.559\,e^{-0.0737n} \quad \text{for } R = 0.1 \\ \beta &= 0.1185 + 3.782\,e^{-0.0857n} \quad \text{for } R = 0.5 \end{aligned} \tag{24}$$

with the correlation coefficient of $r^2 \geq 0.991$.

For the nonnormalized expression, equation (11) can be used to reduce equation (21) to

$$\ln t_f = -n' \frac{\sigma_{max}}{S_i} + \chi \tag{25}$$

where

$$\chi = \ln\left(\frac{a_i}{A}\right) + \beta \tag{26}$$

Therefore, the parameters n' and χ in cyclic stress loading for a given R-ratio can be obtained from the slope and intercept by a linear regression analysis of the data of $\ln t_f$ as a function of σ_{max} or σ_{max}/S_i. With n' calculated, the true SCG parameter n can be evaluated from equation (22). The SCG parameter A can be estimated from equation (26) with calculated χ and β (eq. (24)) along with known values of a_i. A notable difference in cyclic stress loading between the power-law and exponential formulations is that in the power-law formulation t_f is a function of σ_{max} as seen in equation (3), whereas in the exponential formulation $\ln t_f$ is a function of σ_{max} or σ_{max}/S_i as seen in equation (25). Hence, as in the cases of both constant stress rate (refs. 3 and 4) and constant stress loading, the inert strength of a material must be known in cyclic loading beforehand to determine the major SCG parameter n, again a definite disadvantage of the exponential formulation as compared with the power-law formulation.

Experimental Verification

Constant Stress Testing

Time to failure as a function of applied stress in constant stress testing for various ceramics (refs. 19 to 22 and S.R. Choi, 2000, 1993, and 1991, NASA Glenn Research Center, Cleveland, OH, unpublished work) over a wide range of temperatures is shown in figure 3, where σ was plotted against $\ln t_f$ in accordance with equation (19) in the exponential formulation.[a] The decrease in time to failure with increasing

[a] Time to failure is a dependent variable whereas (maximum) applied stress is an independent variable; thus, ideally the resulting plots should reflect this, as in figures 1 or 2. However, the convention is reversed such that (maximum) applied stress is plotted with respect to time to failure. All figures in figure 3 and those that follow use this convention for generality.

applied stress, which represents the susceptibility to slow crack growth, is dependent on material type and test temperature. The individual SCG parameters n and χ were determined from the slope and intercept by the linear regression analysis of ln t_f versus σ based on equation (19), together with inert strength (listed in table I) and the relationship of equation (16). The resulting SCG parameters and the correlation coefficients in regression analysis for individual materials under various test conditions are shown in table II. Figure 4 presents the power-law counterpart plots based on the conventional relation of equation (2). The corresponding SCG parameters n and D and the correlation coefficients for the power-law case are also listed in table II. Comparing the results in figures 3 and 4 together with the correlation coefficients in table II reveals no significant difference in data fit between the exponential and power-law formulations: The exponential formulation resulted in as good a data fit as that of the power-law formulation.

TABLE I.— SUMMARY OF SLOW-CRACK-GROWTH (SCG) PARAMETER A FOR VARIOUS BRITTLE MATERIALS IN CONSTANT STRESS AND CYCLIC STRESS LOADING USING BOTH EXPONENTIAL AND POWER-LAW CRACK-VELOCITY FORMULATIONS

[Data shown have been obtained from previous work (refs. 18 through 22). SEPB (single edge precracked beam) technique was used in fracture toughness evaluation in accordance with ASTM C1421.]

Material[a]	Test Conditions		Fracture toughness, K_{IC}, MPa/m	Inert strength,[b] S_i, MPa	SCG parameter A, m/s	
					Formulation	
	Type of test	Temperature, °C			Exponential	Power-law
Al_2O_3	Constant	Ambient	3.4	295	5.23×10^{-33}	370
Al_2O_3 (indented)	↓	Ambient	3.4	196	1.25×10^{-25}	0.73
NCX34 Si_3N_4		1200	6.9	805	2.33×10^{-17}	2.20×10^{-3}
NCX34 Si_3N_4		1300	6.9	805	3.15×10^{-15}	3.37×10^{-3}
NCX34 Si_3N_4 (tension)		1200	6.9	633	1.22×10^{-12}	1.43×10^{-5}
NC203 SiC		1300	4.0	655	2.58×10^{-14}	1.90×10^{-3}
Al_2O_3		1000	3.4	295	5.53×10^{-12}	.07
Ceralloy 147A Si_3N_4		1200	5.8	600	9.53×10^{-12}	3.90×10^{-4}
Ceralloy 147A Si_3N_4	↓	1200	5.8	600	3.55×10^{-13}	.02
Al_2O_3	Cyclic	Ambient	3.4	295	1.94×10^{-21}	0.03
Al_2O_3 (indented)	↓	Ambient	3.4	196	8.02×10^{-24}	2.20
NCX34 Si_3N_4		1200	6.9	805	6.92×10^{-19}	2.42×10^{-3}
NCX34 Si_3N_4	↓	1300	6.9	805	3.91×10^{-17}	.52

[a]Al_2O_3 is alumina; Si_3N_4, silicon nitride; and SiC, silicon carbide.

[b]Inert strength was determined at ambient temperature in oil for SCG-susceptible materials (alumima) and in air for SCG-insensitive material (including most silicon nitrides and silicon carbides). Previous studies on ultrafast strength behavior of various advanced ceramics at elevated temperatures showed that strength at ultrafast test rates of 10^4 to 10^5 MPa/sec converged and was close to room-temperature inert counterparts (e.g., ref. 26 in summary). Consequently, as close approximation, room-temperature inert strength was used as elevated-temperature inert strength in evaluating parameter A. Most inert strength data is quoted from reference 26.

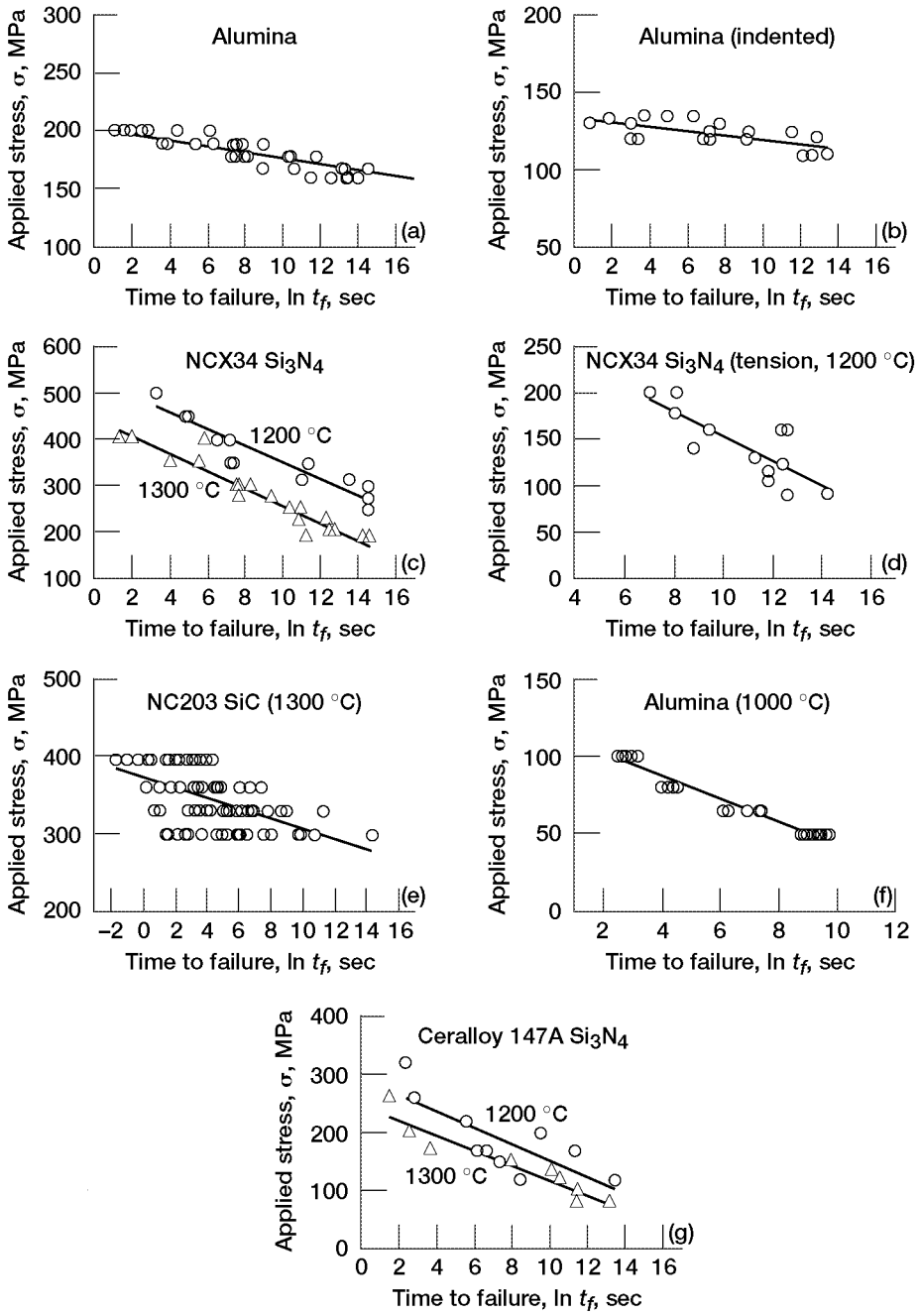

Figure 3.—ln (time to failure) versus applied stress σ for various ceramics with exponential crack-velocity formulation using equation (19) under constant stress loading. Solid lines represent best fit. (a) Alumina in ambient distilled water in flexure (S.R. Choi, 2000, NASA Glenn Research Center, Cleveland, OH, unpublished work). (b) Alumina (indented) in ambient distilled water in flexure (ref. 19). (c) NCX34 (Norton Co., Worcester, MA) silicon nitride at 1200 and 1300 °C in air in flexure (ref. 20 and S.R. Choi, 1993, NASA Glenn Research Center, Cleveland, OH, unpublished work). (d) NCX34 silicon nitride at 1200 °C in air in tension (ref. 20). (e) NC203 (Norton Co., Worcester, MA) silicon carbide at 1300 °C in air in flexure (ref. 21). (f) Alumina at 1000 °C in air in flexure (ref. 22). (g) Ceralloy 147A (Ceradyne, Inc., Costa Mesa, CA) silicon nitride at 1200 and 1300 °C in air in flexure (S.R. Choi, 1991, NASA Glenn Research Center, Cleveland, OH, unpublished work).

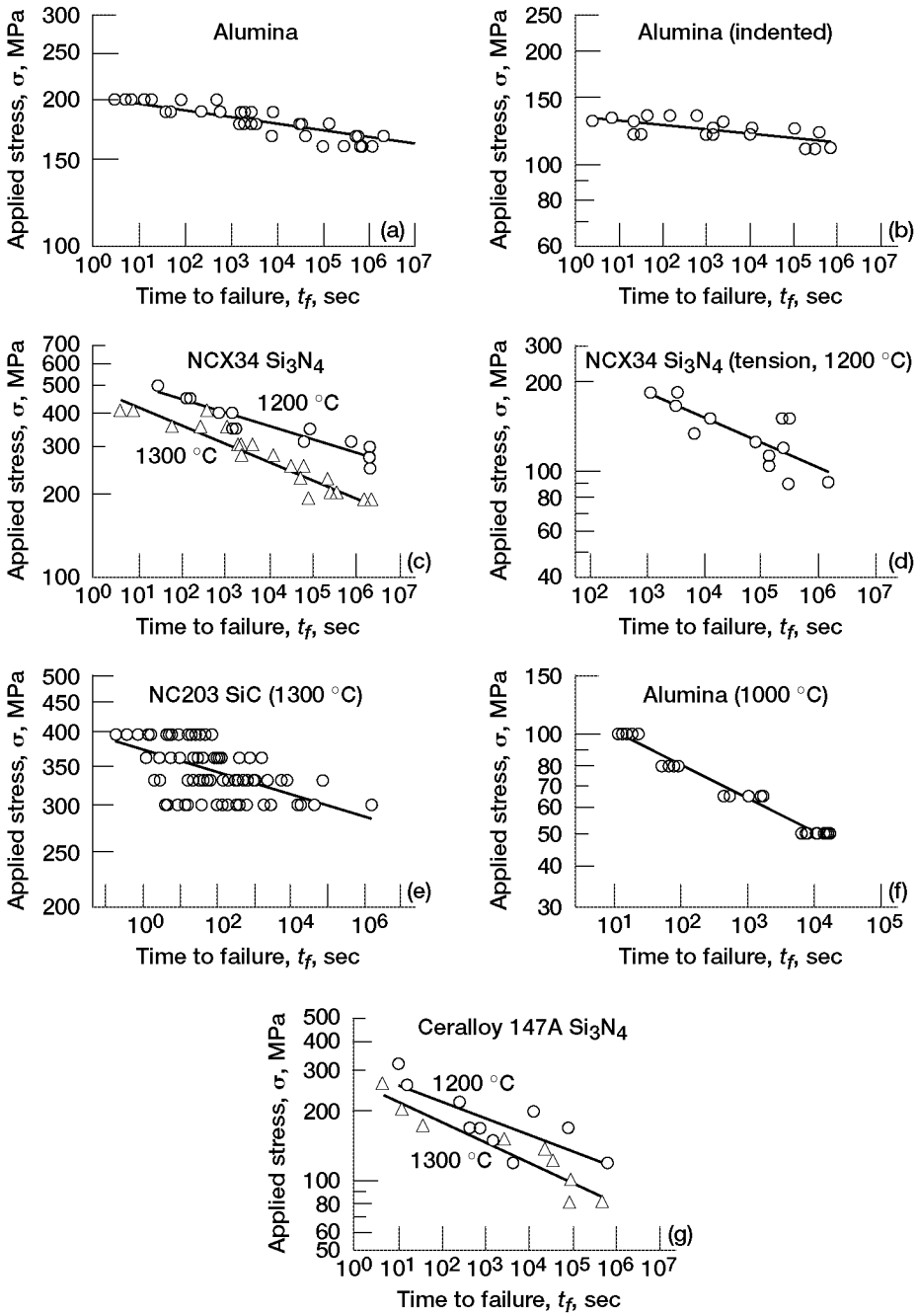

Figure 4.—Time to failure t_f as function of applied stress σ or various ceramics with power-law crack-velocity formulation using equation (2) under constant stress loading. Solid lines represent best fit. (a) Alumina in ambient distilled water in flexure (S.R. Choi, 2000, NASA Glenn Research Center, Cleveland, OH, unpublished work). (b) Alumina (indented) in ambient distilled water in flexure (ref. 19). (c) NCX34 silicon nitride at 1200 and 1300 °C in air in flexure (ref. 20 and S.R. Choi, 1993, NASA Glenn Research Center, Cleveland, OH, unpublished work). (d) NCX34 silicon nitride at 1200 °C in air in tension (ref. 20). (e) NC203 silicon carbide at 1300 °C in air in flexure (ref. 21). (f) Alumina at 1000 °C in air in flexure (ref. 22). (g) Ceralloy 147A silicon nitride at 1200 and 1300 °C in air in flexure (S.R. Choi, 1991, NASA Glenn Research Center, Cleveland, OH, unpublished work).

TABLE II.—SUMMARY OF SLOW-CRACK-GROWTH (SCG) PARAMETERS AND CORRELATION COEFFICIENTS OF DATA FIT FOR VARIOUS BRITTLE MATERIALS USING BOTH EXPONENTIAL AND POWER-LAW CRACK-VELOCITY FORMULATIONS IN CONSTANT STRESS AND CYCLIC STRESS LOADING

[Mode of tests was in four-point flexure.]

Material[a]	Test conditions		Formulation						Reference
			Exponential			Power-law			
	Type of test	Temperature,[b] °C	SCG parameter,[c] n_e	SCG parameter,[d] χ	Correlation coefficient,[e] r^2	SCG parameter, n_p	Log D[d]	Correlation coefficient,[e] r^2	
Al_2O_3	Constant	Ambient	87.6	63.3181	0.7541	54.5	126.7306	0.7538	(f)
Al_2O_3 (indented)		Ambient	61.0	47.3313	.4367	39.7	86.3279	0.4411	19
NCX34 Si_3N_4		1200	37.3	27.4263	.8837	18.5	51.3172	0.8955	20
NCX34 Si_3N_4		1300	36.3	22.5133	.9055	13.5	36.7292	0.8988	(g)
NCX34 Si_3N_4 (tension)[h]		1200	27.0	17.5694	.6278	6.4	18.3751	0.6024	20
NC203 SiC		1300	27.6	20.2295	.3058	7.7	42.2076	0.3013	21
Al_2O_3		1000	36.3	15.6789	.9638	15.9	20.3067	0.9798	22
Ceralloy[i] 147A Si_3N_4		1200	22.9	15.5657	.6094	9.6	22.5671	0.6051	(j)
Ceralloy[i] 147A Si_3N_4		1300	38.8	17.9811	.8927	8.6	25.0071	0.8860	(j)
Al_2O_3	Cyclic	Ambient	45.9	38.7877	0.6299	10.1	77.5788	0.6356	23
Al_2O_3 (indented)		Ambient	59.5	44.7325	.7936	32.5	77.4315	0.7925	19
NCX34 Si_3N_4		1200	41.6	32.0421	.8027	20.8	58.5654	0.7815	24
NCX34 Si_3N_4		1300	52.3	27.9453	.7872	17.5	46.8061	0.7631	(g)

[a]Al_2O_3 is alumina, Si_3N_4 is silicon nitride, and SiC is silicon carbide.
[b]Testing at ambient temperature was performed in distilled water.
[c]Inert strength listed in table II was used in calculating n in exponential formulation.
[d]SCG parameters χ and D were determined with units of time to failure in seconds and stress in megapascals.
[e]r^2 indicates square of correlation coefficient.
[f]S.R. Choi, 2000, NASA Glenn Research Center, Cleveland, OH, unpublished work.
[g]S.R. Choi, 1993, NASA Glenn Research Center, Cleveland, OH, unpublished work.
[h]Tests for NCX34 (tension) were performed in tension rather than in flexure.
[i]Ceradyne, Inc., Costa Mesa, CA.
[j] S.R. Choi, 1991, NASA Glenn Research Center, Cleveland, OH, unpublished work.

Cyclic Stress Testing

Figure 5 shows previous results of cyclic stress testing for alumina and NCX34 silicon nitride (refs. 19, 23, 24, and S.R. Choi, 1993, NASA Glenn Research Center, Cleveland, OH, unpublished work) where σ_{max} was plotted against ln t_f based on equation (25) in the exponential formulation for each material under given test conditions.[a] As in constant stress testing, the materials exhibited the decrease in time to failure with increasing maximum applied stress, indicative of susceptibility to SCG. The SCG parameters n and χ were determined from the slope and intercept by linear regression of ln t_f versus σ_{max}, based on equation (25) together with inert strength (listed in table I) and the relationship of equation (22). The SCG parameters thus evaluated and the correlation coefficients in regression analysis are listed in table II. Figure 6 presents the counterpart plots of the experimental data using the power-law formulation (equation (3)). Similar to the case of constant stress testing, there was no significant difference in data fit between the exponential and power-law formulations. Hence, both the exponential and power-law formulations would give an equally reasonable data fit, so a choice of SCG formulations would not make any difference in terms of the degree of data fit.

Discussion

Relationship Between SCG Parameters n

Because of the functional form of the crack-velocity equation in either the exponential or power-law formulation, the SCG parameter n has the most sensitive and significant effect on lifetime; thus, accurate estimation of n is crucially important and must always be emphasized. In fact, n in the conventional power-law formulation has been used as an important measure of SCG susceptibility of brittle materials: There is significant SCG susceptibility for $n < 30$, intermediate susceptibility for $n = 30$ to 50, and insignificant (or highly resistant to SCG) susceptibility for $n > 50$. Therefore, it is worthwhile to establish the relationship of n in the exponential formulation to that in the power-law formulation, which can be done using the n values from table II determined in constant stress and cyclic stress testing. Figure 7 illustrates the relationship between the SCG parameters n from each formulation. The overall relationship with a total of 13 data points was approximated as follows:

$$n_e = 1.110 n_p + 19.957 \tag{27}$$

with a correlation coefficient of $r^2 = 0.8439$. The n_e and n_p represent the SCG parameter n in exponential and power-law formulations, respectively. The n_e is greater than n_p by approximately 20. Figure 7 also includes the relationship determined from the data in constant stress rate testing (ref. 4), where the corresponding relationship was

$$n_e = 0.964 n_p + 12.524 \tag{28}$$

with $r^2 = 0.9511$. Hence, the two relationships (eqs. (27) and (28)) were not in good agreement, resulting in a difference of about 10 in the values of n_e between them.

This difference in n can be seen more easily if n in constant stress rate loading is plotted against that in constant stress and cyclic loading, which is shown in figure 8. Although the overall relationship between n in constant stress rate loading and n in constant stress and/or cyclic loading seems to be 1:1 in the exponential formulation (fig. 8(a)), the data scatter was significant with a tendency of n to be greater in constant stress and cyclic loading than in constant stress rate loading. The corresponding

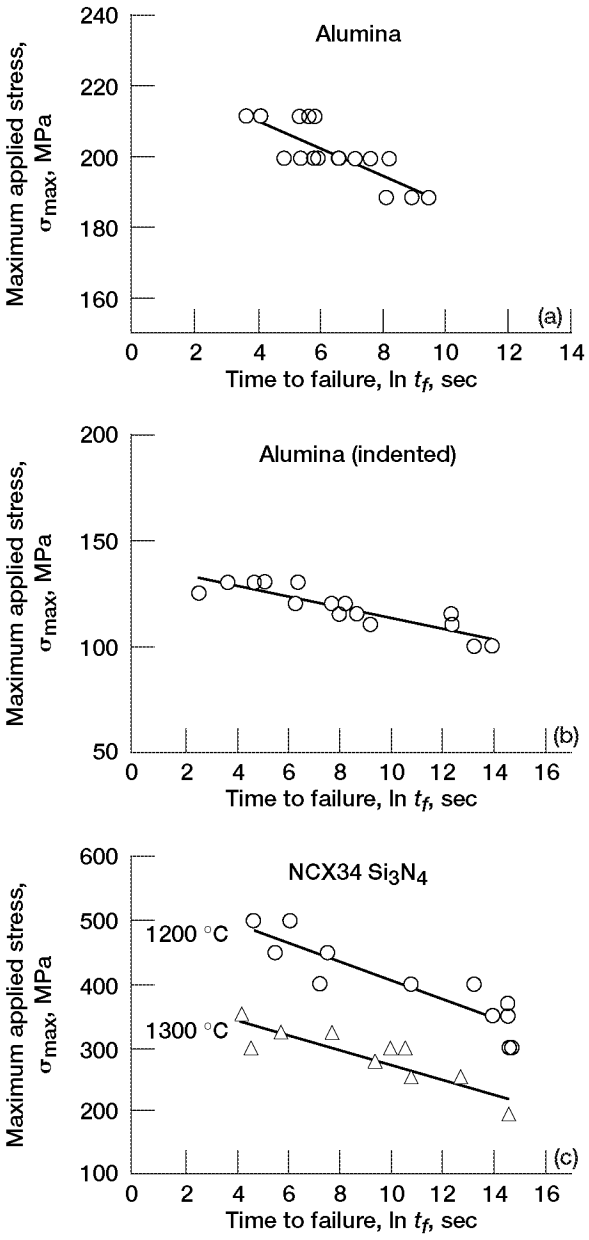

Figure 5.—ln (time to failure) versus maximum applied stress in exponential crack-velocity formulation using equation (25) under sinusoidal cyclic loading. Solid lines represent best fit. (a) Alumina in ambient distilled water in flexure (R = 0.1) (ref. 23). (b) Alumina (indented) in ambient distilled water in flexure (R = 0.5) (ref. 19). (c) NCX34 silicon nitride at 1200 (ref. 24) and 1300 °C (S.R. Choi, 1993, NASA Glenn Research Center, Cleveland, OH, unpublished work) in air in flexure (R = 0.5).

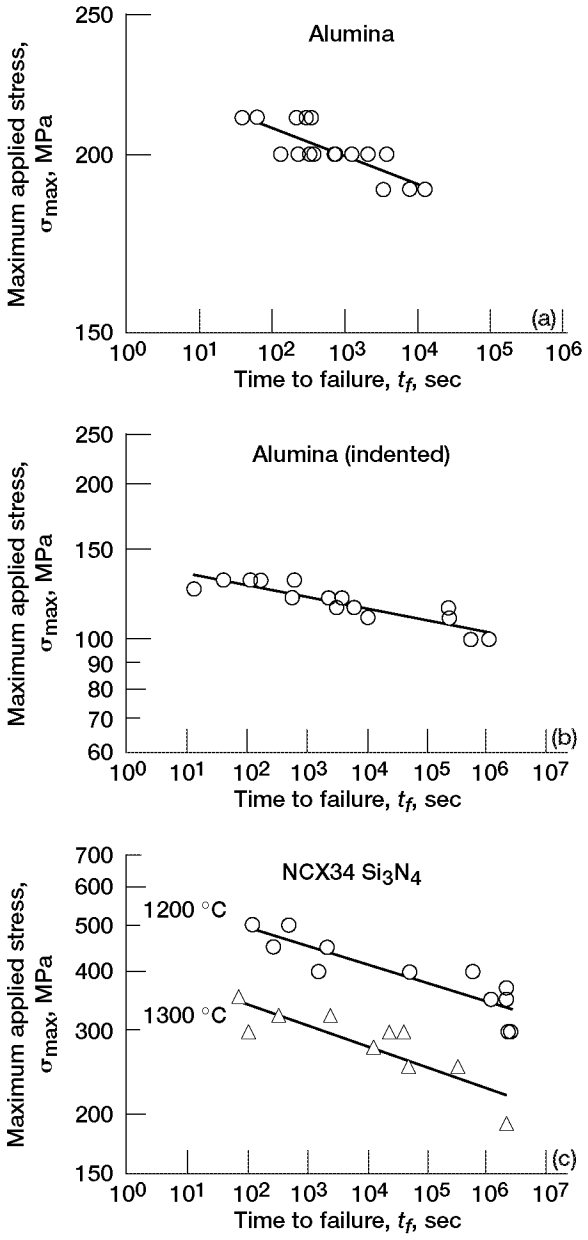

Figure 6.—log (time to failure) versus log (maximum applied stress) for various ceramics with power-law crack-velocity formulation using equation (3) under sinusoidal cyclic loading. Solid lines represent best fit. (a) Alumina in ambient distilled water in flexure (R = 0.1) (ref. 23). (b) Alumina (indented) in ambient distilled water in flexure (R = 0.5) (ref. 19). (c) NCX34 silicon nitride at 1200 °C (ref. 24) and 1300 °C (S.R. Choi, 1993, NASA Glenn Research Center, Cleveland, OH, unpublished work) in air in flexure (R = 0.5).

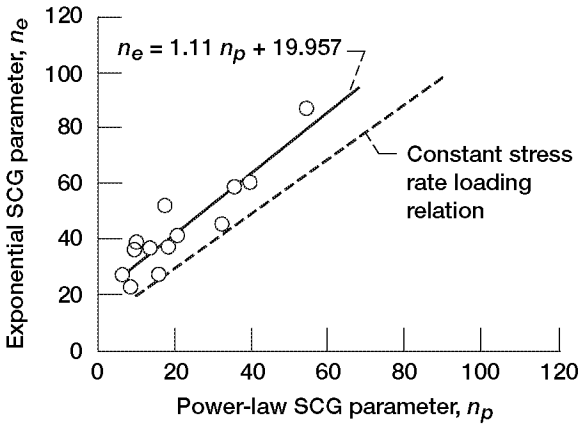

Figure 7.—Relationship of slow-crack-growth (SCG) parameter of exponential formulation n_e to that of power-law formulation n_p for various materials from table II for constant stress and cyclic loading. Relationship determined for constant stress rate loading (ref. 4) included for comparison.

relationship in the power-law formulation (fig. 8(b)), however, yields good agreement between constant stress rate loading and constant-stress/cyclic loading, which has been typical of many advanced ceramics observed at Glenn for decades. The reason for less agreement in the exponential formulation is not yet clear and requires more data. It is believed to result from inaccurate values of inert strength of the materials because the SCG parameter n is determined from both the slope of the time to failure versus stress relation (regression analysis) and the inert strength (eq. (19) or (25)). Note that n in the power-law formulation is determined solely from the slope of the relations with stress (eq. (2) or (3)).

SCG Parameter A and Crack Velocity

The parameter A can be determined using experimental data based on equations (20) and (26) for constant stress and cyclic stress loading, respectively, in the exponential formulation, whereas the respective parameter A in the power-law formulation can be determined from equations (4) and (5) with the B expression. The initial crack size or the critical crack size in the inert condition a_i can be estimated using the fundamental relation of $K_{IC} = Y S_i a_i^{1/2}$, assuming the crack configuration to be a semicircle ($Y = 2/\sqrt{\pi}$) and the crack size to be small compared with components or test coupons (i.e., an infinite-body approach). The resulting A parameters for each material thus estimated for both the exponential and power-law formulations are shown in table I. Unlike the SCG parameter n, no definite relationship existed for A between the two formulations, which was similar to that observed in constant stress rate loading (ref. 4). Notwithstanding, the actual crack velocities for a given stress intensity factor seem not much different from each other with some exceptions, as can be seen from the results of log v versus K_I/K_{IC} in figure 9. Each crack velocity for a given K_I/K_{IC} was calculated using A and n from their respective crack-velocity formulas—equation (6) for the exponential formulation and equation (1) for the power-law formulation.

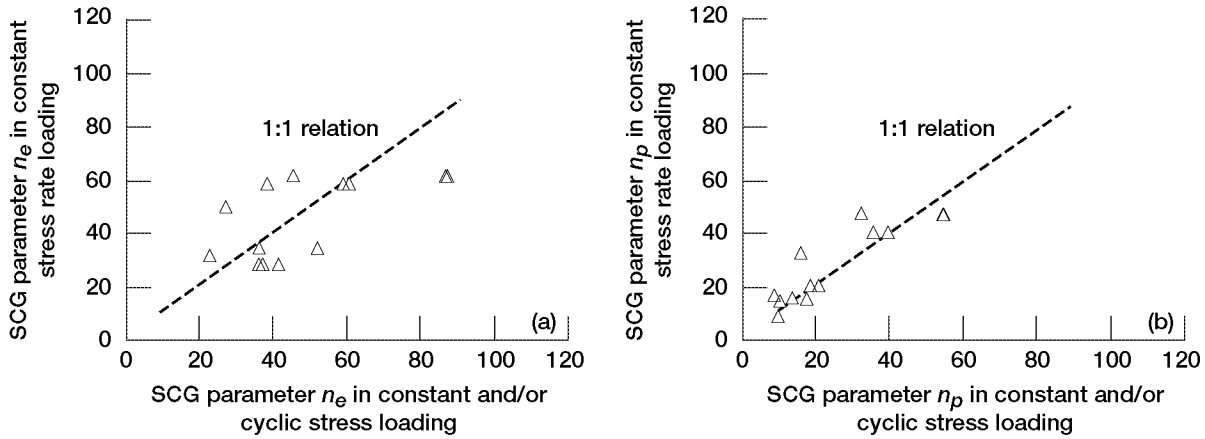

Figure 8.—Relationship between slow-crack-growth (SCG) parameters n in constant stress rate loading and those in constant stress and/or cyclic stress loading. SCG parameters n for constant stress-rate loading were obtained from previous study (ref. 4). (a) Exponential crack-velocity formulation. (b) Power-law crack-velocity formulation.

Life Prediction From Static Loading to Cyclic Loading

The ratio of constant stress to cyclic stress lives, h-ratio, for the condition of σ in constant stress loading equal to σ_{max} in cyclic stress loading ($\sigma = \sigma_{max}$) has been frequently used in the power-law formulation (refs. 6, 18, and 25) to compare lives of static and cyclic loading or to predict life from one loading configuration to another. The h-ratio is defined as

$$h = \frac{t_{fs}}{t_{fc}} \tag{29}$$

where t_{fs} and t_{fc} are times to failure, respectively, in constant stress and cyclic stress loading. The h-ratio in the exponential formulation has been numerically determined in cyclic loading with different R-ratios as a function of n from a previous study (ref. 3), and its results are presented in figure 10(a). The h-ratio decreases with increasing SCG parameter n, and the rate of decrease with increasing n is almost the same regardless of the R-ratio up to 0.9. Also for a given n, the h-ratio increases with increasing R-ratio. Note that the ratio of $R = 1.0$ represents the case for constant stress loading. The h-ratio varies slightly by a factor of 2 for σ^*_{max} between 0.2 and 0.9: the lower σ^*_{max} yields the higher h-ratio and vice versa. Hence, for a conservative estimation, the higher value of $\sigma^*_{max} = 0.7$ was used in the calculation of h-ratio (ref. 3). A very similar trend in h-ratio was also found previously in the power-law formulation, as shown in figure 10(b) (ref. 18). Unlike the exponential formulation, the power-law formulation revealed no effect of σ^*_{max} on the h-ratio for a given R-ratio.

Figure 11(a) shows examples of lives predicted from the constant stress data (fig. 3) for a cyclic loading configuration for alumina at ambient temperature and for NCX34 silicon nitride at elevated temperatures using the solution shown in figure 10(a). The prediction did not seem to be in good agreement with the actual cyclic stress data. However, if one considers that scatter in time to failure in either constant stress or cyclic stress testing for most machined ceramics is usually significant, typically 2 or 3 orders of magnitude, the prediction and the experimental data are in reasonable agreement since the deviation is still within 1 order of magnitude. The counterpart plots of prediction using the power-law formulation (fig. 10(b)) are shown in figure 12. By comparing figures 11 and 12, one can conclude readily that the exponential and the power-law formulations result in almost the same degree of accuracy in life prediction for each given material and test conditions.

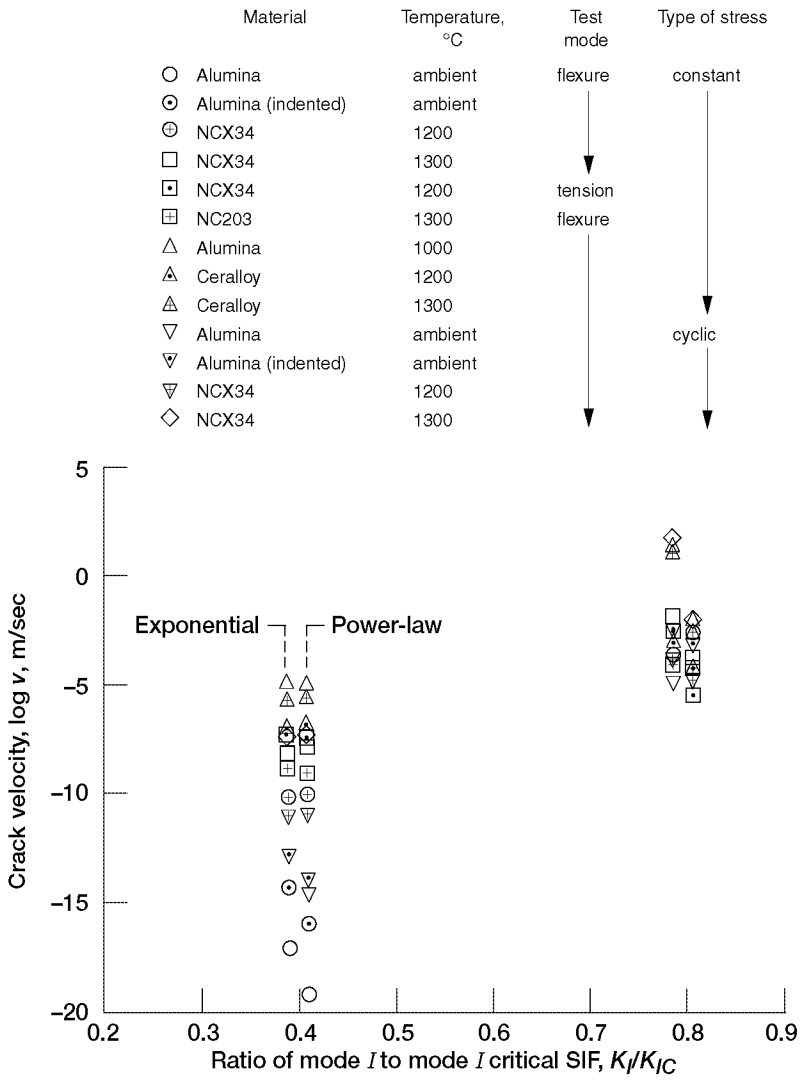

Figure 9.—Comparison of crack velocity as function of stress intensity factor (SIF) K_I/K_{IC} in both exponential and power-law formulations for materials used in this report.

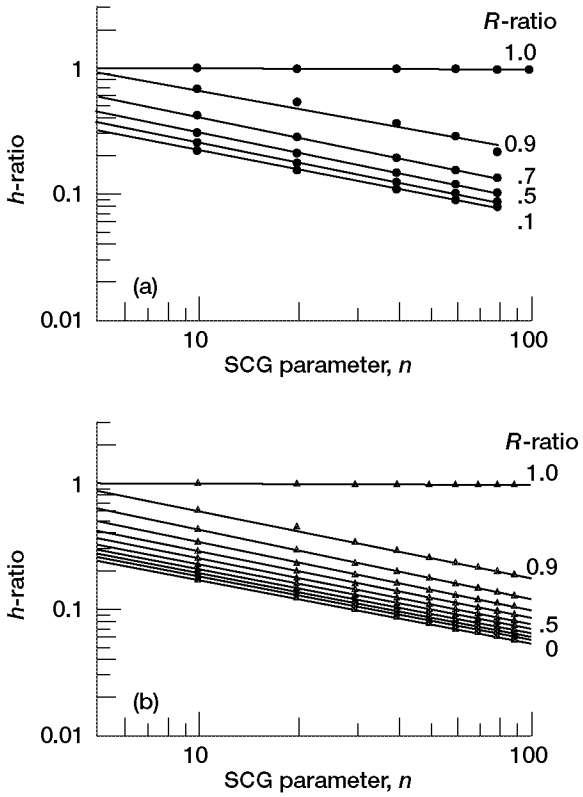

Figure 10.—*h*-ratio as function of SCG parameter *n* for different values of *R*-ratio. Each line represents best fit. (a) Exponential crack-velocity formulation (ref. 3). (b) Power-law crack-velocity formulation (ref. 18).

Limitation of Exponential Formulation

Although the exponential formulations used to determine SCG parameters required somewhat inconvenient numerical procedures (ref. 3), their resulting solutions under a constant stress rate loading condition had shown to yield almost the same degree of simplicity in data analysis as well as in the agreement in experimental data as those in the power-law formulation (ref. 4). The same was true for constant stress and cyclic stress loading conditions, as appeared from the present results. However, that the inert strength of a material must be known beforehand to determine the major SCG parameter n can be a major drawback and/or obstacle in using the exponential formulation in terms of simplicity and accuracy, as compared with the power-law formulation, which does not require knowledge of the inert strength. Inert strength of a material at room temperature, of course, is not difficult to determine; however, even in this case care must be exercised to provide a perfect inert condition by using appropriate conditions (environment and test rate) so that an accurate inert strength can be evaluated. A greater burden would be determining inert strength at elevated temperatures, although the authors have done pioneering work in this subject using a total 17 advanced ceramics (see ref. 26 for summary) with some conclusive results that the elevated-temperature inert strength of a ceramic material can be estimated with an ultrafast test rate of $\geq 10^5$ MPa/sec and that the elevated-temperature inert strength is close to that of the room-temperature. However, this finding has not yet been finalized, and a more valid data base needs to be established.

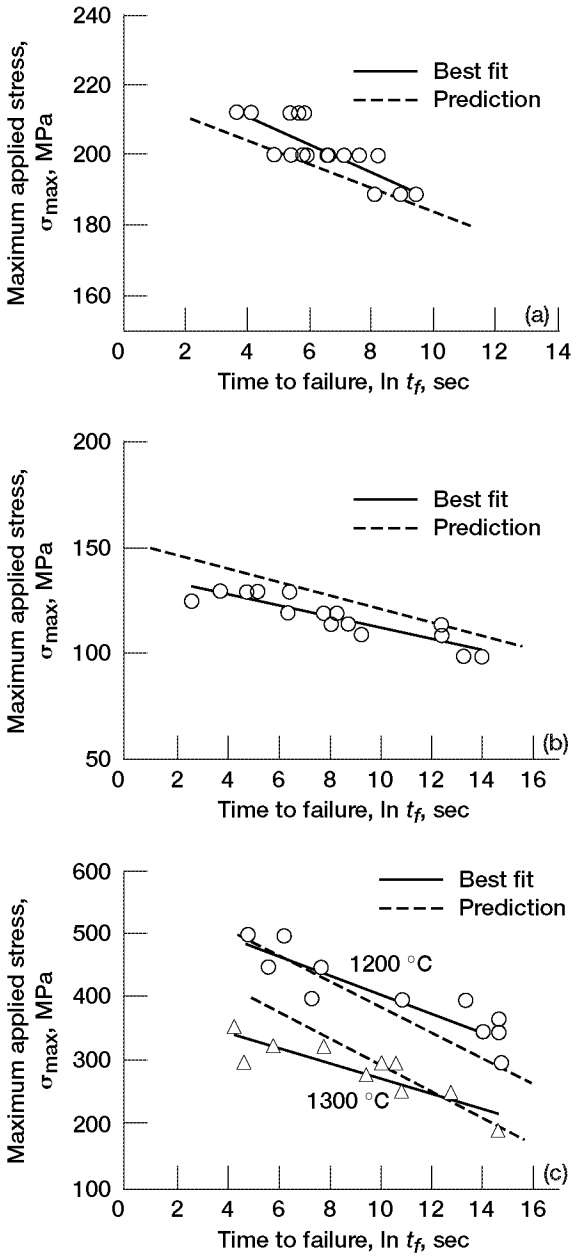

Figure 11.—Life prediction in sinusoidal cyclic loading from constant stress loading data with exponential crack-velocity formulation (eq. (28) and fig. 10 (a)). (a) Alumina in ambient distilled water in flexure (ref. 26 and S.R. Choi, 2000, NASA Glenn Research Center, Cleveland, OH, unpublished work). R = 0.1. (b) Alumina (indented) in ambient distilled water in flexure (ref. 20). R = 0.5. (c) NCX34 silicon nitride at 1200 and 1300 °C in air in flexure (refs. 20, 24, and S.R. Choi, 1993 and 1991, NASA Glenn Research Center, Cleveland, OH, unpublished work). R = 0.5.

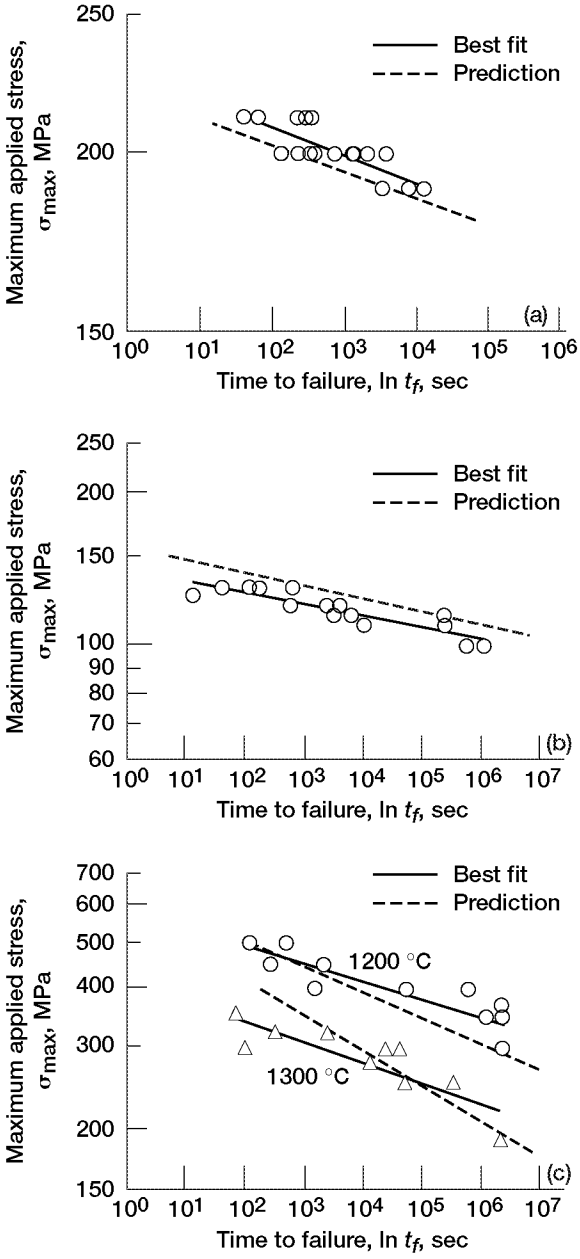

Figure 12.—Life prediction in sinusoidal cyclic loading from constant stress loading data with power-law crack-velocity formulation (eq. (28) and fig. 10 (b)). (a) Alumina in ambient distilled water in flexure (ref. 26 and S.R. Choi, 2000, NASA Glenn Research Center, Cleveland, OH, unpublished work). R = 0.1. (b) Alumina (indented) in ambient distilled water in flexure (ref. 19). R = 0.5. (c) NCX34 silicon nitride at 1200 and 1300 °C in air in flexure (refs. 20, 24, and S.R. Choi, 1993 and 1991, NASA Glenn Research Center, Cleveland, OH, unpublished work). R = 0.5.

Conclusions

1. The data fit to the ln (*time to failure*) versus (*maximum*) *applied stress* relation in the exponential crack-velocity formulation under constant stress or cyclic stress loading was found very reasonable for most of the advanced ceramics used.

2. The relationship of slow-crack-growth (SCG) parameters n determined with the exponential formulation n_e, to those determined with the power-law formulation n_p was comparable under both constant stress and cyclic stress loading. However, this relationship was not similar to those determined under constant stress rate loading.

3. Life prediction in the cyclic stress loading configuration from constant stress loading data was in good agreement with the actual cyclic stress experimental data. The prediction in the exponential formulation was almost identical in terms of accuracy to that in the power-law formulation.

4. Despite little difference both in the data fit from one loading configuration to another, the major limitation in the requirement of knowledge of inert strength in evaluating the SCG parameter n makes the power-law formulation a more preferable choice for life prediction and SCG parameter determination than the exponential formulation.

Appendix—Symbols

A	slow-crack-growth parameter defined in equations (1) and (6)
a	crack size
B	slow-crack-growth parameter, $B = 2K_{IC}/[AY^2(n-2)]$
C	crack size in normalized scheme of references 16 to 18
D	slow-crack-growth parameter defined in equations (4) and (5)
$f(t)$	periodic function, cyclic loading
h	ratio of constant to cyclic stress loading lifetimes
K	stress intensity factor
n	slow-crack-growth parameter defined in equations (1) and (6)
R	stress ratio
r^2	correlation coefficient
S	strength, MPa
T	time in normalized scheme of references 16 to 18
t	time, sec
v	crack velocity
Y	crack geometry factor
β	intercept of curve in linear regression analysis
χ	slow-crack-growth parameter defined in equation (20)
σ	applied stress, MPa
τ	period
ω	angular velocity

Subscripts:

C	critical

c	cyclic stress
e	exponential formulation
f	fracture
I	mode I
i	inert or initial condition
max	maximum
min	minimum
p	power-law formulation
s	constant stress

Superscripts:

*	normalized
′	apparent (calculated)

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13. ABSTRACT ***(Maximum 200 words)***

The previously determined life prediction analysis based on an exponential crack-velocity formulation was examined using a variety of experimental data on advanced structural ceramics tested under constant stress and cyclic stress loading at ambient and elevated temperatures. The data fit to the relation between the time to failure and applied stress (or maximum applied stress in cyclic loading) was very reasonable for most of the materials studied. It was also found that life prediction for cyclic stress loading from data of constant stress loading in the exponential formulation was in good agreement with the experimental data, resulting in a similar degree of accuracy as compared with the power-law formulation. The major limitation in the exponential crack-velocity formulation, however, was that the inert strength of a material must be known a priori to evaluate the important slow-crack-growth (SCG) parameter n, a significant drawback as compared with the conventional power-law crack-velocity formulation.

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